Thermal tests of the solar oven.

Fig. 1. The solar oven. Front left: The outer box. Front right: The inner box. Behind: The window.

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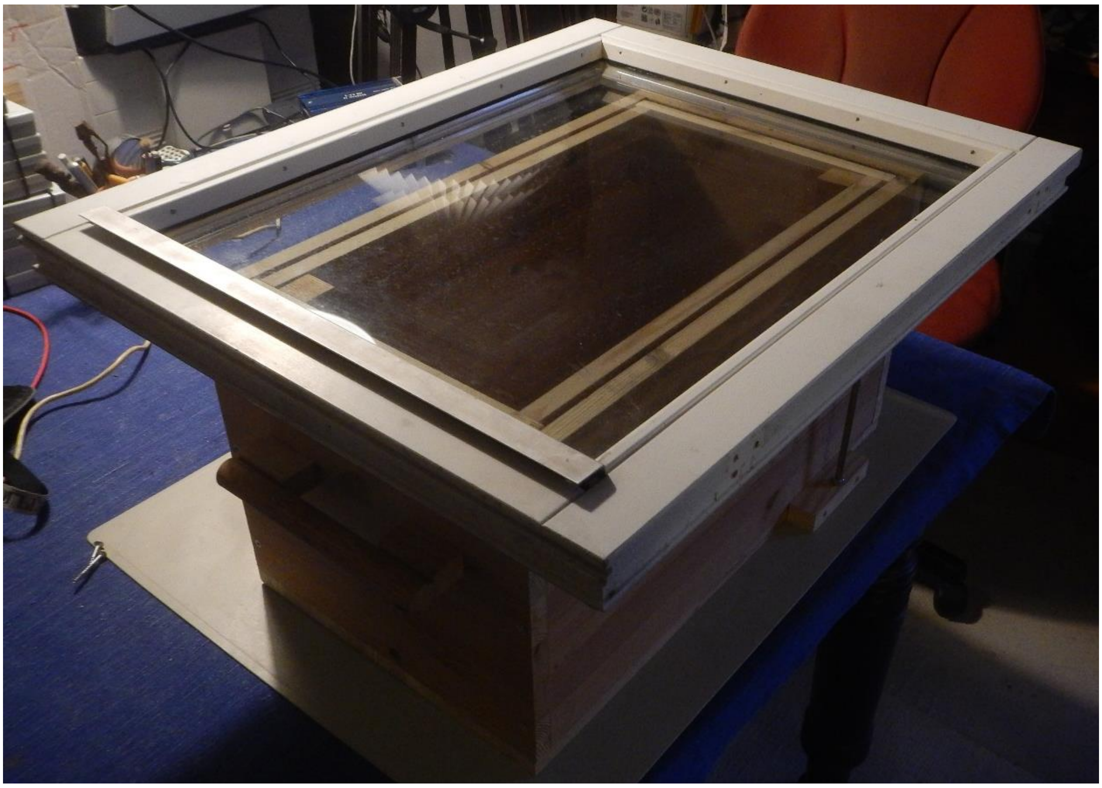

Fig. 2. The solar oven with the window on top.

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Thermal tests of the solar oven revision 2.

1. Introduction. This report describes the thermal test of the solar oven revision 2 - built in August 2024. The aim is – based on the thermal measurements at the oven – to find out – for a given irradiation - how much the solar oven can rise its temperature T above the temperature of the ambient T_{Amb}. - and how fast it can do it.
For that we a. need to find the thermal resistance R_{Th} between the interior of the solar oven and the ambient – and b. and the time constant τ of the oven.

To avoid the influence of unpredictable weather, and allow the test to be carried out indoor, the test has used reversed heat flows to measure the resistances and thermal time constant. By a reversed heat flow measurement, a controllable heating source is placed inside the solar oven and the resulting increase in the temperature difference between the interior of the box and the ambient is measured. The controllable electrical heating source is adjusted to emulate the irradiation P of the solar power.

After the heating source is switched on, the temperature (as function of the elapsed time) is recorded, and the recordings are used to calculate the thermal time constant and the resistance of the oven.

After having heated the oven to a certain temperature and recorded the measured temperatures of the oven – the oven has been switched off and the falling temperatures (as a function of the elapsed time after switch off) have been recorded.

Recording the falling temperature - rather than the rising temperature - has the advantage, that by the falling temperature we know both the starting temperature and what the final temperature of the oven will be – as the final temperature will be identical to the temperature of the ambient (i.e. the room in which the measurements take place). Opposite, by measuring the rising temperatures we know the starting temperature (which must be identical to the ambient temperature – but it will take infinitely long to obtain the final temperature.

We also want to find the time it will take the oven to heat up to a certain temperature. For this we must find the thermal time constant τ for the oven and employ the relation that $\tau = R_{Th} \times C_{Th}$,
where R_{Th} is the thermal resistance between the interior of the oven and the ambient
- and C_{Th} is the thermal capacitance between the interior of the oven and the ambient.

2. The thermal parameters of a solar oven by rising and by falling temperatures.

2.1. The thermal capacitance (C_{Th}) is one of the thermal parameters. It describes a body's ability to store energy in the form of heat. Its unit is energy per degree Centigrade [J/^{o}C] or energy per Kelvin [J/K]. If we wish for the oven to heat up (- and to cool down-) quickly, the oven must have to have a low thermal capacitance.

2.2. The transient temperature response and the thermal time constant. Assume that - as a start - the oven has the same temperature as the surroundings. Then, at the time t = 0, it is placed in the sun. If there is no difference in the temperature ΔT (between the inside of the oven and the surroundings), no heat will pass between the oven and the surroundings. Hence, all the power / heat from the sun will be converted into an increasing temperature- and stored in the thermal capacitance - i.e. the oven and its contents. In other words: The energy is now stored in the thermal capacitance of the oven (including its contents of kitchen utensils, food and water etc.). This might be difficult to comprehend, hence, why it is explained in different ways.

At the time t = 0, the rate of the rise in temperature per time unit (dT/dt) will be determined by the solar power P divided by the total thermal capacity C_{Th} of the oven and its contents. Thus, the more water and/or food (i.e. the higher a thermal capacitance) which is placed in the oven, the longer will it take to raise its temperature.

As the temperature of the oven and its contents rises, the difference between a. the temperature inside the oven and b. the ambient temperature outside the oven - increases. This will cause a bigger part of the heat from the sun to flow from the oven, (through the thermal resistance) to the surroundings. Therefore, less and less solar power will be left over to heat the oven and its contents. Hence, – as can be seen at the figure below - the more the temperature of the oven with its contents (asymptotically) approaches its final temperature T_{Final} – the less power will be left over for "charging" the thermal capacitance. Thus, the temperature of the oven will rise slower and slower.

Ultimately (after an eternally long time) - as the temperature in the solar oven has stabilised - the irradiated power from the sun to the oven will be the same as the power leaving the oven to the surroundings - and the temperature will stop rising.

In other words - during the time it takes to establish this balance / equilibrium between the in-going and the out-going power, a still smaller part of the solar power going to the oven, can / will be used for heating the oven and its contents (i.e. food, pots etc.). And - during the very same time, it takes for this balance / equilibrium to be established, an increasingly bigger part of the solar power, which enters the oven, will be "lost", i.e. it goes from the oven to the surroundings.

2.2. The temperature as a function of the time for a rising temperature.

Physically - and mathematically - it can be expressed as: The final temperature of the oven will be equal to the ambient temperature ($T_{Amb.}$) plus the solar power (P) multiplied by the thermal resistance (R_{th}) between the interior of the oven and the ambient $T_{Final} = T_{Amb.} + P \times R_{Th}$.

Mathematically the rising temperature of the oven *as a function of the time* can be expressed as:

$$T(t) = T_{Amb.} + (P \times R_{Th}) (1 - e^{-t/(Rth\ Cth)}) = T_{Amb.} + (P \times R_{Th}) (1 - e^{-t/\tau}) \quad - \quad \text{where}$$

T(t) is the temperature of the oven and its contents at the time t after the oven was exposed to the sun.
$T_{Amb.}$ is the ambient temperature (i.e. the temperature of the surroundings).
P is the solar power, which enters the oven.
R_{Th} is the thermal resistance between the interior of the oven and the ambient (i.e. the surroundings).
C_{Th} is the thermal capacitance of the interior of the oven and its contents.
τ is the thermal time constant, and $\tau = R_{Th} \times C_{Th}$.

The shape of the temperature as a function of time T(t) (marked V_{CAP}) is shown at fig. 3.
The horizontal axis represents the time t. The vertical axis represents the temperature T.
The crossing between the horizontal and the vertical axis is t = 0 and $T = T_{Amb}$.
The violet curve (V_{CAP}) shows how the temperature of the oven asymptotically approaches

$$T_{Final} = T_{Amb.} + P\ R_{Th}.$$

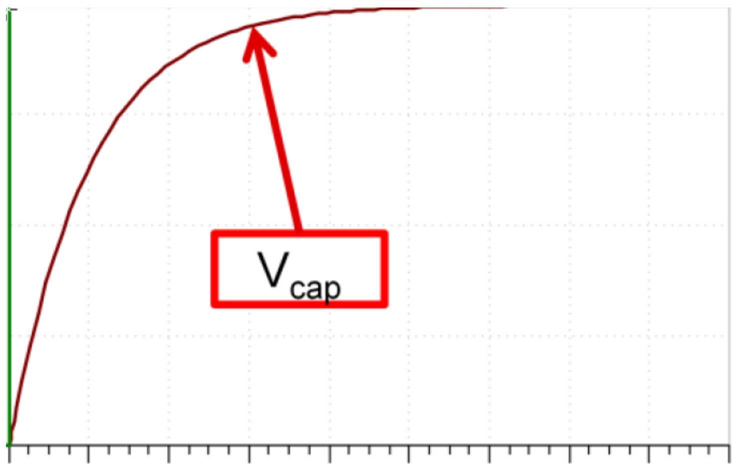

Fig. 3. Rising temperature (T) as a function of time (t).

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If we calculate $(1 - e^{-t/(R_{Th\ Rise} C_{Th})})$ for
$t = 1 \cdot R_{Th\ Rise} \cdot C_{Th}$, $2 \cdot R_{Th\ Rise} \cdot C_{Th}$, $3 \cdot R_{Th\ Rise} \cdot C_{Th}$ and $4 \cdot R_{Th\ Rise} \cdot C_{Th}$, - we will get:

$T(K\tau) = T(t) = T_{Amb.} + (P \times R_{Th\ Rise})(1 - e^{-K})$, where K = 1, 2, 3 and 4 – which yields:
$T(1\tau) = T_{Amb.} + 0.632\ (P \times R_{Th\ Rise})$,
$T(2\tau) = T_{Amb.} + 0.865\ (P \times R_{Th\ Rise})$,
$T(3\tau) = T_{Amb.} + 0.950\ (P \times R_{Th\ Rise})$ - and
$T(4\tau) = T_{Amb.} + 0.982\ (P \times R_{Th\ Rise})$.

2.4. The temperature as a function of the time for a falling temperature.
Similar relations apply to situations, where the influx of solar power to the oven is instantly cut off. In that case the temperature of the oven (as a function of time) can mathematically be written as:

$$T(t) = T_{Amb.} + (P \times R_{Th\ Fall})\, e^{-t/(R_{th\ Fall} C_{th})}$$ - shown at fig. 4 below - where

$T(t)$ is the temperature of the oven and its contents at the time t after the oven is no longer exposed.
$T_{Amb.}$ is the ambient temperature (i.e. the temperature of the surroundings).
P is the solar power, to which the oven was exposed just before the exposure stopped.
$R_{Th\ Fall}$ is the thermal resistance between the interior of the oven and the ambient (i.e. the surroundings).
C_{Th} is the thermal capacitance of the interior of the oven and its contents.

The shape of the temperature as a function of time T(t) (marked I_{CAP}) is shown at the fig. 4 below.
The horizontal axis represents the time t. The vertical axis represents the temperature T.
The crossing between the horizontal and the vertical axes is t = 0 and $T = T_{Amb}$. In this case $T_{Amb.} = 0$.
The violet curve shows how the temperature of the oven asymptotically approaches $T_{Final} = T_{Amb}$.

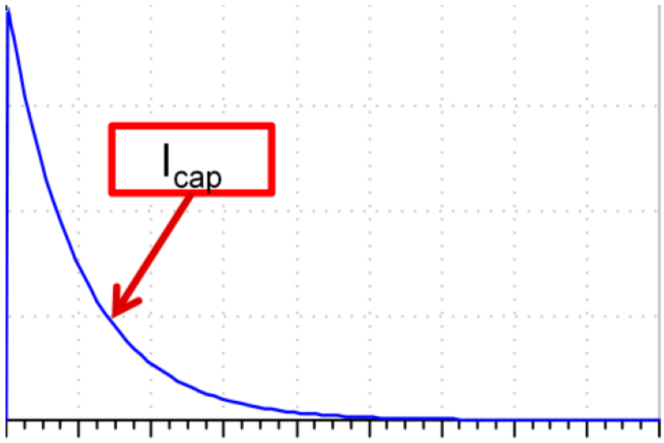

Fig. 4. The falling temperature T as a function of time (t).

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3. The thermal time constant. (τ_{Th}) of the oven with its contents is the product of R_{Th} and C_{Th}.
The thermal time constant τ_{Th} is measured in time units [seconds, minutes, hours or days].
The time constant $\tau_{Th\ Rise}$ is the time it takes for the oven to ***increase*** its temperature from

$T_{Amb.}$ to $T_{Amb.} + (T_{Final} - T_{Amb.})\ (1 - e^{-1}) = T_{Amb.} + 0.632\ (T_{Final} - T_{Amb.})$.

However, the time constant $\tau_{Th\ Fall}$ is the time it takes for the oven to ***decrease*** its temperature from T_{Start} to $e^{-1}\ (T_{Start} - T_{Amb}) = T_{Start} + 0.368\ (T_{Start} - T_{Amb.})$.
A thermal system consisting of a thermal resistance R_{Th} and a thermal capacitance C_{Th}, will have a time constant τ_{Th} equal to $R_{Th} \cdot C_{Th}$.
By a rising temperature, the system will have reached a temperature equal to 63.2% of its total change in temperature after *one* $\tau_{Rise,}$ - 86.5 % after *two* τ_{Rise} - and 95% of its total change in temperature after *three* τ_{Rise}.

For a falling step in the power supplied to the system the system will have reached a temperature equal to: 36.8% of its total change in temperature after *one* τ_{Th} - and
will have reached 5% of its total change in temperature after *three* τ_{Th}.

As we will see - if not all the parameters of the systems remain constant the time τ_{Rise} constant for the ***increasing*** temperature might not be the same as τ_{Fall} for the ***decreasing*** temperature.

4. The test set up.
The power source in the test set up were based on three power resistors connected in parallel - each with a rating of 50W and a resistance of 75 Ω – and were mounted on a heatsink with a thermal resistance of ca. 0.6 K/W. The heatsink and (- to stir the air in the oven) - a 24V / 0,25A / 6 W fan were mounted in the solar oven together with a 0.1 K temperature sensor. The resistors were supplied with 2.09 A (/ 56 V) from an adjustable dual power supply, which other output supplied the fan with 24 V. The temperature was recorded by a Fluke 189 meter.

The solar oven (version 2) comprises two boxes. The outer box is sized 508 x 300 mm - and the inner box has an aperture (i.e. the area of the window opening into the inner box) of: 433 mm x 223 mm = 96559 mm^2.
The area of the two squared handles inside the inner box is – 2 x 30 mm x 30 mm = -1800 mm^2 = 94759 mm^2.
A solar intensity of 1300 W/m^2 through an aperture of 0.0948 m^2 gives an irradiated solar power = 123 W.
To emulate a solar power of 123 W we have a power resistor dissipation of 117 W + a fan power of 6.0 W.
(56.0 V x 2.09 A = 117 W.) The wires for the resistors, the fan and the multimeter are connected inside the boxes through two Ø = 5.0 mm coaxial holes in the end walls of the inner- and the outer box.

One set of tests were made with bare- / unpainted and uncovered (wooden) sides and uncovered window.
One set of tests were made under the same condition but with the window covered with aluminium foil.
One set of tests were made under the same condition but with the window covered with alu. foil and a blanket.
When nothing else is noted the test sets were made with readings taken every 30 minutes.

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5. Test of the plain solar oven - without any aluminium foil or other insulation.

5.1. Rising temperature.

Time: 2024.09.14	17.30	18.00	18.30	19.00	19.30	20.00	20.30
Temperature in Oven T [ºC]	22.7	58.4	73.5	83.1	88.4	93.1	96.8
Ambient Temperature T_{Amb} [ºC]	22.7	22.7	22.7	22.7	22.7	22.7	22.7
Power dissipated in oven [W]	123	123	123	123	123	123	123
T_N - T_{Amb} [ºC]	0	35.7	50.8	60.4	65.7	70.4	74.1
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Table 5. The final measurement T7 = 98,1 ºC, was taken at 21,00.

(If T7 had been the final temperature, $R_{Th\ Rise}$ would have been = (98.1 ºC – 22.7 ºC) / 123W = 0.613 K/W.)

First I use a calculating method, which links $R_{Th\ Rise}$ and τ_{Rise} to two temperature readings taken at t_N and t_{2N}. (N is an integer).
(The method is described in detail in my report: ”Considerations, design calculations, construction, test and evaluation of a cavity walled solar oven” , dated: “Steen Carlsen; Aarhus, Denmark December 16th 2022”.)

Calculations based on the temperature readings at **t_1 and t_2**: t_1
$A_{12} = T_1^2 / (2T_1 – T_2) = (35.7\ K)^2 / (2 \times 35.7\ K - 50.8\ K) = 61.9.\ K.$
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0\ Min.) / (\ln (35.7\ K/ (50.8\ K – 35.7\ K))) = 34.9\ min.$
$T_{Amb} + A = T_{Final} = 22.7$ ºC + 61.9 K = 84.6 ºC.$R_{Th\ Rise}$= ΔT/P =84.6 K / 123 W = 0.688 K/W.

Calculations based on the temperature readings at **t_2 and t_4**:
$A_{24} = T_2^2 / (2T_2 – T_4) = (50.8\ K)^2 / (2 \times 50.8\ K - 65.7\ K) = 71.9\ K.$
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2))) = (60.0\ Min.) / (\ln (50.8\ K/ (65.7 - 50.8\ K))) = 48.9\ min.$
$T_{Final} = T_{Amb} + A$ =22.7 ºC + 71.8 K = 94.5 ºC.$R_{Th\ Rise}$ = ΔT/P = 71.9 K / 123 W = 0.584 K/W.

Calculations based on the temperature readings at **t_3 and t_6**:
$A_{36} = T_3^2 / (2T_3 – T_6) = (60.4\ K)^2 / (2 \times 60.4\ K – 74.1\ K) = 78.1\ K.$
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (90.0\ Min.) / (\ln (60.4\ K/ (74.1\ K - 60.4\ K))) = 133.5\ min.$
$T_{Final} = T_{Amb} + A$ = 21.2 ºC + 78.1 K = 99.3 ºC.$R_{Th\ Rise}$ = ΔT/P = 78.1 K / 123 W = 0.635 K/W.

The values obtained for $R_{Th\ Rise}$ appear very plausible; but the variations in the calculated values of τ_{12}, τ_{24} and τ_{36} indicate that the parameters are nonlinear and the results for τ_{XY} cannot be trusted.

Secondly I apply the method, where I use the measurements of Table 5. to subjectively estimate the final temperature. Looking at the measurements taken indicates that the final temperature T_{Final} is somewhere in the order of 100 ºC.
At $T(\tau) = T_{Amb.} + (T_{Final} - T_{Amb.}) (1 – e^{-1}) = T_{Amb.} + 0.632 (T_{Final} - T_{Amb.})$.
= 22.7 ºC. + 0.632 (100 ºC – 22.7 ºC). = 71.6 ºC

The 71.6 ºC is reached τ_{Rise} after the start of the heating. Using interpolation and the measured temperatures from table 5 we find τ_{Rise} = (18.30 - 17.30) – 30 min. x (73.5 ºC – 71.6 ºC) / (73.5 ºC – 58.4 ºC) = 56,13 min. = 3368 s.

$T_{Amb.} + (T_{Final} - T_{Amb.}) (1 – e^{-1}) = T_{Amb.} + (T_{Final} - T_{Amb.}) \times 0.632.$

We know that $T_{Amb.}$ = 22.7 ºC - and we know that: if T_{Final} = 100 ºC and τ = 3368 s – then:
$T(1\tau) = T_{Amb.} + 0.632 (P \times R_{Th})$ = 71.6 ºC
$T(2\tau) = T_{Amb.} + 0.865 (P \times R_{Th})$ = 89.6 ºC
$T(3\tau) = T_{Amb.} + 0.950 (P \times R_{Th})$ = 96.1 ºC
$T(4\tau) = T_{Amb.} + 0.982 (P \times R_{Th})$ = 98.6 ºC

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Hence, if my estimation of the final temperature T_{Final} = 100 °C is correct and T(τ) = 71.6 °C - then
T(2τ) = (then after 2 x 3368 s) $T_{Amb.}$ + 0.865 (P x R_{Th}) = 22.7. °C + 0.865 x 77.3 K = 89,6 °C – and
T(3τ) = (then after 3 x 3368 s) $T_{Amb.}$ + 0.950 (P x R_{Th}) = 22.7. °C + 0.950 x 77.3 K = 96,1 °C – and
T(4τ) = (then after 4 x 3368 s) $T_{Amb.}$ + 0.982 (P x R_{Th}) = 22.7. °C + 0.982 x 77.3 K = 98,2 °C.

The results of the calculations above are now compared to the readings from table 5:
T(2τ) = 2 x 3368 s = 6736 s = 112.26 min = 1 hour and 52,26 min = 2 hours minus 7.74 min. =
T(6736s) = 88,4 °C – (88.4 °C - 83,1 °C) x (7.74 min / 30 min) = 87.0 °C.

T(3τ) = 3 x 3368 s = 10104 s = 168.4 min = 2 hours and 48,4 min = 3 hours minus 11.6 min. =
T(10104s) = 96.8 °C – (96.8 °C - 93.1 °C) x (11.6 min / 30 min) = 95.4 °C.

The ratio between the calculated and the measured P(2τ) = (89,6 °C - 22.7 °C) / (87.0 °C - 22.7 °C) = 1.04 x
The ratio between the calculated and the measured P(3τ) = (96.1 °C - 22.7 °C) / (95.4 °C - 22.7 °C) = 1.01 x.

- Hence, for T_{Final} = 100 °C, R_{Th} = (T_{Final} - $T_{Amb.}$) / P = (100.0 °C - 22.7 °C) / 123 W = 0.628 K/W.
- Which corresponds well with our assumption.

A third calculation of C_{Th} uses the initial slope of the temperature of the oven (ΔT/Δt) – just after it has started to increase from T_{Amb}. (Note that: e = 2.718; $e^{-0} = e^0 = 1.000$ and $e^{-1} = 1/e = 0.372$).

$T(t) = T_{Amb.} + (P \times R_{th\ Rise})\,(1 - e^{-t/(R_{th\ Rise} C_{th})})$
The initial slope of T(t) for t = 0 can be found by differentiate T(t) (written as T(t)'), and insert t = 0.
$T(t)' = \Delta T / \Delta t$
$= d\,(T_{Amb.} + (P \times R_{th\ Rise})\,(1 - e^{-t/(R_{th\ Rise} C_{th})})) / dt$
$= (P \times R_{th\ Rise}) \times (e^{-t/(R_{th\ Rise} C_{th})}) \times (1/(R_{Th\ Rise}\, C_{Th}))$
$= (T_{Final} - T_{Amb.}) \times (1/\tau_{Rise}))$
$= (T_{Final} - T_{Amb.}) / \tau_{Rise}$
= (100.0 °C - 22.7 °C) / 3368 s => T(0)' = 0.0230 K/s

C_{Th} = ΔE / ΔT = (Δt x P) / ΔT = P / T(0)' = 123 W/ 0.0230 K/s = = 5363 J/K

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5.2. Falling temperature.
On September 14th 2024 at 21.40 (= 9.40 p.m.) the temperature of the oven had reached 100.0 ^oC, and I switched off the power supply, which had supplied the fan and the heating of the oven.

Not until some days after I had taken the first measurements of the falling temperature of the oven, did I realise the impact, which the fan has on the thermal time constant τ_{Fall} and $R_{Th\ Fall}$. The power supply, which supplies the power resistors, also supplies the fan. I realised that when the fan is running it stirs up the air of the inner box and thereby increases the convection, which decreases the thermal resistance between the oven and the ambient.

C_{Th} is determined by the masses and the material of the oven.
Neither of these two parameter change when we change between rising and falling temperature.
Hence, the oven will have the same thermal capacitance C_{Th} by rising as by falling temperature - but both the time constant τ and the thermal resistance R_{Th} will change - depending on whether the power resistors and the fan are switched on – or not. To reduce confusion, the time constant and thermal resistance will be denoted "Rise" when the power resistors and the fan are switched on - and "Fall" when not.

Time: 2024.09.14	21,40	22.15	23.00	23.17	23.28	00.07	
Temperature in Oven T [^oC]	100.0	70.0	53.4	48.7	43.7	39.7	.
Ambient Temperature T_{Amb} [^oC]	22.7	22.7	22.7	22.7	22.7	22.7	22.7
Power dissipated in oven [W]	123	123	123	123	123	123	123
T_N - T_{Amb} [^oC]	0	35.7	50.8	60.4	65.7	70.4	74.1
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Table 6 - provides the temperature readings for the cooling off of the oven.

The cooling of the oven starts at t_0 = 21.40 at a temperature of 100 ^oC,
and we know that the final temperature T_{Final} will be the same as the ambient temperature T_{Amb}.
We also know that after one time constant τ_{Fall} the temperature will have sunk to

$T(\tau_{Fall}) = T_{Amb} + (P \times R_{Th\ Fall})\ e^{-\tau/(R_{Th\ Fall}\ C_{Th})} \quad = \quad T_{Amb} + 0.368\ (T_{Start} - T_{Amb.})$
$= 22.7\,^oC + 0.368\ (100\,^oC - 22.7\,^oC) \quad =>$ $\quad T(\tau_{Fall}) = 51{,}1\,^oC$.

Based on the readings of table 6 and using interpolation I find that $T(\tau_{Fall}) = 51{,}1\,^oC$.
$T(\tau_{Fall}) = 51{,}1\,^oC$ will be reached after:
(23.00 – 21.40) + (23.17 – 23.00) (53.4 ^oC - 51,1 ^oC) / (53.4 ^oC – 48.7 ^oC) =
60 min. + 20 min. + 17 min. x (2.3 K /4.7 K) = τ_{Fall} = 88.3 min. => $\quad \tau_{Fall}$ = 5298 s.

We can therefore use the value we found for C_{Th} for the rising temperature.
$C_{Th\ Fall} = C_{Th\ Rise}$ = 3368 s / 0.628 K/W = 5363 J/K

$C_{Th} = \Delta E/\Delta T = P \times \Delta t / \Delta T = \tau_{Fall} / R$. Based on C_{Th} and τ_{Fall}, I then find $R_{Th\ Fall}$.
$R_{Th\ Fall} = \tau_{Fall} / C_{Th}$ = 5298 s / 5363 J/K = 0.988 K/W

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6. Using the solar oven as a hey box.

When there is no sun the solar oven can be used as a hay box to keep food and liquids warm. In that situation very little solar power is irradiated into the oven through the window. At the same time a part of the heat in the oven will be radiated from the oven to the ambient. The amount of heat - lost as radiation from the oven through the window to the ambient - can be reduced by covering the window with a blank aluminium foil. The aluminium foil will work as a mirror, reflecting a part of the heat radiated from the oven back into the oven.

6.1 Rising temperature with aluminium foil on top of the window.

Time: 2024.09.15	8.30	9.00	9.50	10.00	10.30	11.00	11.30
Temperature in Oven T [ºC]	21.9	57.7	81.1	83.8	90.9	95.3	98.2
Ambient Temperature T_{Amb} [ºC]	21.9	22	22	22	22	22	22
Power dissipated in oven [W]	123	123	123	123	123	123	123
T_N - T_{Amb} [ºC]	0	35.8	59.2	61.9	69.0	73.4	76.3
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Table 7 shows the measurements on the solar oven when the window is covered with aluminium foil.
At the time t_7 = 11.55 the temperature reached T_7 = 100C. 2.09A 54.64V.

The reading at 9.30 was lost, which is why the two calculations based on the readings at t_1 were omitted.

Calculations based on the temperature readings at **t_3 and t_6**:

$A_{36} = T_3^2 / (2T_3 – T_6) = (61.9\ K)^2 / (2 \times 61.9\ K – 76.3\ K) = 77.4\ K.$

$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (90.0\ Min.) / (\ln (61.9\ K/ (76.3\ K - 61.9\ K))) = 131.2\ min.$

$T_{Final} = T_{Amb} + A = 21.9\ ^oC + 77.4\ K = 99.3\ ^oC$.$R_{Th\ Rise} = \Delta T/P = 77.4\ K / 123\ W = 0.629\ K/W.$

Knowing that:

$T(\tau) = T_{Amb.} + (T_{Final} - T_{Amb.}) (1 – e^{-1}) = T_{Amb.} + 0.632 (T_{Final} - T_{Amb.}).$

$= 21.9\ ^oC + 0.632 (99.3\ ^oC – 21.9\ ^oC)$

$= 70.8\ ^oC$

The temperature $T(\tau)$ =71.6 ºC is reached at the time τ after the start of the heating.
Using interpolation and the measured temperatures from table 7 we find:

τ_{Rise} = (9.00 - 8.30) + (9.50 – 9.00) x (70.8 ºC – 57.7 ºC) / (88.1 ºC – 57.7 ºC) = 51,5 min. = 3092 s.

Assuming that the mass of aluminium foil can be regarded as insignificant, and with all other parameters of the oven are identical to the parameters in the first measurements, the C_{Th} found in the first measurements also applies here: C_{Th} = 5363 J/K.

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6.2. Falling temperature with aluminium foil on top of the window.

Time: 2024.09.15:	11,55	12,19	13.24	14.32	14.55	15.40	16.50
Temperature in Oven T [°C]	100,0	77.4	51.9	39,00	36,2.	32.1	28.2
Ambient Temperature T_{Amb} [°C]	21.7	22	22	22	22	22	22
Power dissipated in oven [W]	123	123	123	123	123	123	123
T_N - T_{Amb} [°C]	78.3	55.4.	29.9	17.0	14.2.	10.1	6.2.
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Table 8. window covered with aluminium foil
The cooling of the oven starts at t_0 = 11.55 at a temperature of 100 °C,
and we know that the final temperature T_{Final} will be the same as the ambient temperature T_{Amb}.

We also know that after one time constant τ_{Fall} the temperature will have sunk to:

$T(\tau_{Fall}) = T_{Amb} + (P \text{ x } R_{Th\ Fall})\ e^{-\tau/(R_{Th\ Fall}\ C_{Th})} = T_{Amb} + 0.368\ (T_{Start} - T_{Amb.})$
= 22. °C + 0.368 (100 °C – 22 °C) => $T(\tau_{Fall})$ = 50,7 °C.

Based on the readings of table and using interpolation I find that $T(\tau_{Fall})$ = 50,7 °C
will be reached after: (13.24 -12.19) + (14.32 - 13.24) (51.9 °C – 50.7) / (51.9 °C - 39,0 °C) =
65 min. + 68 min. x (1.2 K / 12.9 K) = τ_{Fall} = 71.3 min. => τ_{Fall} = 4280 s.

C_{Th} = 5363 J/K.

Based on C_{Th} and τ_{Fall}, I then find R_{Th}. $R_{Th\ Fall} = \tau_{Fall} / C_{Th}$ = 4280 s / 5363 J/K = 0.798 K/W.

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7.1. Rising temperature with both aluminium foil and a blanket on top of the window.
To get a sense of how much heat was lost through the window, I placed eight layers of thick blanket on top of the aluminium foil on top of the window, and took down the readings.

Rising temperature with both aluminium foil and blanket. 54,44 V & 2,09 A

Time: 2024.09.16	11.00	11.30	12.00	12.30	13.00	13.30	14.00
Temperature in Oven T [ºC]	22.3	57.2	73.0	83.7	90.8	96.1	100,0
Ambient Temperature T_{Amb} [ºC]	21.7	22	22	22	22	22	22
Power dissipated in oven [W]	123	123	123	123	123	123	123
T_N - T_{Amb} [ºC]	0.6	35.2	51.0	61.7	68.8	74.1	78.0
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Table 9. Rising temperature with both aluminium foil and blanket.

Calculations based on the temperature readings at **t_1 and t_2**: t_1
$A_{12} = T_1^2 / (2T_1 – T_2)$ = (35.2 K)^2 / (2 x 35.2 K - 51.0 K) = 63.9 K.
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1)))$ = (30.0 Min.) / (ln (35.2 K/ (51.0 K – 35.2 K))) = 24.0 min.
T_{Amb} + A = T_{Final} = 22. ºC + 63.9 K = 85.9 ºC.$R_{Th\ Rise}$= ΔT/P = 63.9 K / 123 W = 0.52 K/W.

Calculations based on the temperature readings at **t_2 and t_4**:
$A_{24} = T_2^2 / (2T_2 – T_4)$ = (51.0 K)^2 / (2 x 51.0 K – 68.8 K) = 78.3 K.
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2)))$ = (60.0 Min.) / (ln (51.0 K/ (68.8 - 51.0 K))) = 57.0 min.
T_{Final} = T_{Amb} + A = 22 ºC + 78.3 K = 100.3 ºC.$R_{Th\ Rise}$ = ΔT/P = 78.3 K / 123 W = 0.637 K/W.

Calculations based on the temperature readings at **t_3 and t_6**:
$A_{36} = T_3^2 / (2T_3 – T_6)$ = (61.7 K)^2 / (2 x 61.7 K – 78.0 K) = 83.9 K.
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3)))$ = (90.0 Min.) / (ln (61.7 K/ (78.0 K - 61.7 K))) = 67.6 min.
T_{Final} = T_{Amb} + A = 22 ºC + 83.9 K = 105.9 ºC.$R_{Th\ Rise}$ = ΔT/P = 83.9 K / 123 W = 0.682 K/W.

Where the last two values obtained for $R_{Th\ Rise}$ appear to be very plausible - the variations in the calculated values of τ_{12}, τ_{24} and τ_{36} indicate that the parameters are too nonlinear and the results for τ_{XY} should not be trusted.

Knowing that:
$T(\tau) = T_{Amb.} + (T_{Final} - T_{Amb.}) (1 – e^{-1}) = T_{Amb.} + 0.632 (T_{Final} - T_{Amb.})$.
= 22.0 ºC. + 0.632 (105.9 ºC – 22.0 ºC). = 75.0 ºC.

The temperature T(τ) = 75.0 ºC is reached at the time τ after the start of the heating.
Using interpolation and the measured temperatures from fig. we find:
τ_{Rise} = (12.00 - 11.00) - (12.30 – 12.00) x (75.00 ºC – 73.0 ºC) / (83.7 ºC – 73.0 ºC) = 54,4 min. = 3263 s.

Assuming that the mass of aluminium foil can be regarded as insignificant, and with all other parameters of the oven are identical to the parameters in the first measurements, the C_{Th} found in the first measurements also applies here: C_{Th} = 5363 J/K.

Based on C_{Th} and τ_{Fall}, I then calculate R_{Th}. $R_{Th\ Fall} = \tau_{Fall}/ C_{Th}$ = 3263 s / 5363 J/K = 0.608 K/W.

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7.2. Falling temperature with both aluminium foil and a blanket on top of the window.

Time: 2024.09.16	14.01	14.30	15.00	15.30	16.00	16.30	17.00
Temperature in Oven T [ºC]	100.0	75.1	62.7	54.2	47.9	43.1	39.3
Ambient Temperature T_{Amb} [ºC]	21.7	22	22	22	22	22	22
Power dissipated in oven [W]	123	123	123	123	123	123	123
T_N - T_{Amb} [ºC]	78	53.1	40.7	32.2	25.9	21.1	17.3
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Table 10. Falling temperature with both aluminium foil and eight layers of blanket; 54,44 V & 2,09 A.
Additional readings:7.40 pm.: 28,4 ºC; 04.00 am.: 23,0 ºC.

We know that after one time constant τ_{Fall} the temperature will have sunk to
$T(\tau_{Fall}) = T_{Amb} + (P \text{ x } R_{Th\ Fall})\ e^{-\tau/(RTh\ Fall\ \ CTh)} = T_{Amb} + 0.368\ (T_{Start} - T_{Amb.})$
= 22. ºC + 0.368 (100 ºC – 22 ºC) => $T(\tau_{Fall})$ = 50,7 ºC.

Based on the readings of table and using interpolation I find that $T(\tau_{Fall})$ = 50,7 ºC will be reached after
(15.30 - 14.01) + (16.00 - 15.30) (54.2 ºC – 50.7) / (54.2 ºC – 47.9 ºC) =
89 min. + 30 min. x (3.5 K / 6.3 K) τ_{Fall} = 105.7 min. => τ_{Fall} = 6340 s.

C_{Th} = 5363 J/K.

Based on C_{Th} and τ_{Fall}, I then find R_{Th}. $R_{Th\ Fall} = \tau_{Fall} / C_{Th}$ = 6340 s / 5363 J/K = 1.182 K/W

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8. Test results and Conclusion.

The second version of the solar oven has been tested for the most important of its thermal properties, which are:

a. How much it can raise the interior temperature relative to the ambient temperature (R_{Th}) τ_{Fall} – and
b. How fast it can raise the interior temperature (τ).

To find R_{Th} and τ *I used the method*, which links R_{Th} and τ to three temperature readings taken at $t_{0,}$ t_N and t_{2N} (where N is an integer). The method is based on the assumption the temperature as a function of time describes exact exponential curves. The measurements and the calculation shows that the thermal functions are not exact exponential curves, and that the calculated values show that R_{Th} is a little / susceptible to these deviations – jet, no more than they still provide very useful data. The values obtained for τ, however, are so susceptible that in practice the obtained values cannot be trusted.

(The method is described in details in my report: ”Considerations, design calculations, construction, test and evaluation of a cavity walled solar oven” , dated: “Steen Carlsen; Aarhus, Denmark December 16th 2022”.)

For the plain oven (empty, unpainted and uncovered) the obtained value for R_{Th} is 0.628 K/W,
which is somewhat better. (in the order of 10-20%) compared to the first prototype (from 2022).
The thermal time constant was measured and calculated to be 56,1 min.

When the solar oven is used as an oven heat will pass from the sun into the oven.
When the solar oven is used as a hay box, heat will pass from the oven – through the window and out to the ambient.
A piece of aluminium foil was placed on top of the window to reflect the radiation from the oven back into the oven.
The aluminium foil increased the thermal resistance R_{Th} from 0.628 K/W to 0.798 K/W (~ 27%).
The thermal time constant τ_{Fall} was also increased from 56,1 min. to 71.3 min. (~ 27%).

With the same power supplied to the oven – the oven was then covered with eight layers of thick blanket on top of the aluminium foil on top of the window.
This increased R_{Th} from 0.628 K/W to 1.182 K/W (~ 88%).
The thermal time constant τ_{Fall} also increased from 56.1 min. to 105.7 min. (~ 88%).

Finally, I have just discovered that I have made a mistake, which has an impact on virtually all the calculations in this report. I have used the voltage limit, which - while the output of the power supply was switched off - was displayed at the front of the power supply rather than using the voltage and current displayed (54,44 V & 2,09 A) while the output was switched on and the current limiting function was activated.

The power which was supplied to the solar oven by all the measurements was 54,44 V x 2,09 A = 113,8 W.
Thus, the 117 W -which was used in the calculations - was wrong. Hence the results should be corrected by 2.7% (to the better).

The test results of this second version of the solar oven compared to the test results of the first prototype, to me indicate that the present concept of the solar oven prevails.

Steen Carlsen;
Aarhus Denmark
September 25$^{th.}$ 2024.

Insulation: Towel. Time:	04.00	04.33	05.00	05.30	06.00	06.30	07.00
Temperature in Oven T [ºC]	21.5	59.8	73.0	83.1	91.2	96.6	100.0
Ambient Temperature T_{Amb} [ºC]	21.5	22	22	22	22	22	22
Power dissipated in oven [W]	123	123	123	123	123	123	123
T_N - T_{Amb} [ºC]	0	35.7	50.8	60.4	65.7	70.4	74.1
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Kl.7,17: 101,9; Kl. 8,20: 106,1; Kl. 8,30: Switch off 106,5 C; Kl. 8,40: 106,2C

Falling temperature without alu foil and without blanket 2024.09.18

Insulation: Towel. Time:	9.00	09.30	10.00	10.31	11.00	11.30	12.00
Temperature in Oven T [ºC]	105.1	77.1	62.4	51.8	45.2	40.2	36.3
Ambient Temperature T_{Amb} [ºC]	24	24	22	22	22	22	22
Power dissipated in oven [W]	123	123	123	123	123	123	123
T_N - T_{Amb} [ºC]	0	35.7	50.8	60.4	65.7	70.4	74.1
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

12,46: 32,0 Kl.13,00: 31,1 C.   Kl. 13,30: 29,4 C; kl. 14,00 28,2 C kl 15,32 26,3 C

ΔT = 105.1 ºC – 24 ºC = 81,1 K   R = ΔT / P = 81.1 K / 123 W = 0,658 K/W
T (τ) = 105,1 ºC - 81,1 K x 0,632 = 105,1 ºC – 51,26 K = 53.8 ºC. – is reached at
 = 91 min – 31min (53,8-51,8)/(62,4-51,8)
= 91 min – 5,8 min = 85,2 min = τ

8,00 23,3
8,02 23,4
8,03 23,4
8,04 24,6 1,2
8,05 26,8 2,2
8,06 29,4 2,6
8,07 31,5 2,1
8,08 33,6 2,1
8,09 35,4 1,8
8,10 36,9 1,5 12,3 / 6 = 2,05 K/min = 0,0341 K/s
No alu no blanket:

Insulation: Towel. Time:	04.00	04.33	05.00	05.30	06.00	06.30	07.00
Temperature in Oven T [ºC]	21.5	59.8	73.0	83.1	91.2	96.6	100.0
Ambient Temperature T_{Amb} [ºC]	21.5	22	22	22	22	22	22
Power dissipated in oven [W]	123	123	123	123	123	123	123
T_N - T_{Amb} [ºC]	0	35.7	50.8	60.4	65.7	70.4	74.1
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

(59,8 oC – 21,5 C) / 33 min = 0,0193 K/s
(73,0 - 59,8 oC) / 27 min = 0,00814 K/s
(73,0 oC – 21,5 C) / 60 min = 0,0143 K/s

ΔT = ΔE / C => C = ΔE / ΔT = P Δt / ΔT = 123 W / 0,0193 K/s = 6373 J/K
τ = 85,2 min = 5112 s = R x C => R = τ / C = 5112 s / 6373 J/K= 0,802 K/W

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$\Delta T = \Delta E / C \Rightarrow C = \Delta E / \Delta T = P \Delta t / \Delta T$ = 123 W / 0,0143 K/s = 8601 J/K
τ = 85,2 min = 5112 s = R x C => R = τ / C = 5112 s / 6373 J/K= 0,594 K/W

How to obtain the parameters of interest.
From physics it is known that a thermal equivalent of the solar oven can be represented to a thermal capacitance (between the interior of the oven and the ambient). And parallel to that, a thermal resistance (between the interior of the oven and the ambient) - and a heating source to represent the sun.

It is also known that there is an analogy between thermal and electrical properties. Hence, an oven with a thermal capacitance and a thermal resistance can be represented by an electrical capacitance C, an electrical resistance R - and a current source I to represent the sun.

The temperature difference between the oven and its ambient - as a function of the time elapsed after the oven has been exposed to the sun - can therefore be represented as the voltage across the capacitor (or the resistor) in the electrical equivalent (after the current source has been connected to the capacitor).

Again from the physics it is known, that the voltage across the capacitor C (as a function of the time elapsed after the current source has been connected to the capacitor) can be described as:

$$V_C(t) = V_C(0) + I R (1 - e^{-t/(RC)}).$$

- Where $V_C(0)$ is the voltage across C at the time t = 0 when the current source is switched on.

Because of the analogy between the thermal and the electrical world we can now take the expression of the voltage as a function of time – and transferee it from the electrical domain back to the thermal domain. Thus we can and write the expression of the temperature as a function of time – as:

$$T_C(t) = T_C(0) + I R_{Th} (1 - e^{-t/(RTh\ CTh)})$$

- Where $T_C(0)$ is the starting temperature of the oven at the moment the oven is exposed to the sun.
I is the solar power – i.e. the irradiation of the sun (I = P).

We have now derived an expression for the temperature in the oven as a function of the time – for a rising temperature. In order to find R_{Th} we do, however, wish to use the expression for the temperature in the oven as a function of the time – for a falling temperature – which is:

$$T_C(t) = T_C(0) + I R_{Th}\ e^{-t/(RTh\ CTh)}$$

And again $T_C(0)$ is the starting temperature of the oven at the moment the oven is exposed to the sun.
I is the solar power – i.e. the irradiation of the sun (I = P).

Now we can use the measured temperatures as a function of the time together with the temperature in the oven as a function of the time – for a *falling* temperature – to find the time constant τ for the oven; $\tau = R_{Th} C_{Th}$.

Let us assume that at the time t = 0 we have a warm oven with a temperature T_0. T At the time t = 0 the oven starts to cool off. From the expression for the temperature in the oven as a function of the time – for a falling temperature – we know that: $T_C(t) = T_C(0) + I R_{Th}\ e^{-t/(RTh\ CTh)}$.

If we insert t = 0 in the expression $e^{-0/(RTh\ CTh)} = 1$; and $T_C(0) = + I R_{Th}$ e. = T_0.

We know the intensity I of the sun and we have adjusted the power dissipation P in the oven to match I.
Jet – as mentioned earlier – using the expression for the temperature as function of the time it will take infinitely long to obtain the final temperature.

By a falling temperature we can start by measuring the initial temperature in the oven. Here the course of the temperature of the oven starts from a high and approaches asymptotic to the ambient temperature. All though the temperature of the oven takes for ever to settle, we know that it will ultimately settle at the ambient temperature, which we can measure. Thus, we have the full temperature span ΔT, and as we know that at the time t = τ the difference between the temperature in the oven and the ambient temperature equals the full temperature span multiplied by $e^{-1} = 1/e$ = 0,368, we can now find τ as the time when the temperature of the oven has dropped

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$1- e^{-1} = 1 - 1/e = 1 - 0.368 = 0.632 \times \Delta T$.

$$T_C(t) = T_C(0) + I\,R_{Th}\,(1 - e^{-t/(RTh\ CTh)})$$

And for a falling temperature $T(t) = T_{Amb} + I\,R_{Th}\,e^{-t/(RTh\ CTh)} = T_{Amb} + I\,R_{Th}\,e^{-t/\tau}$

At the time t_0 the temperature $T(0) = T_{Amb} + I\,R_{Th}\,e^{-t/\tau} = T_{Amb} + I\,R_{Th}\,e^{-0/\tau} = T_{Amb} + I\,R_{Th} \times 1.000 = T_{Amb} + I\,R_{Th}$
At the time $t_0 = \tau$ the temperature $T(\tau) = T_{Amb} + I\,R_{Th}\,e^{-\tau/\tau} = T_{Amb} + I\,R_{Th}\,e^{-1} = T_{Amb} + I\,R_{Th}\,(1/e)$
$= T_{Amb} + I\,R_{Th}\,/2.718 = = T_{Amb} + I\,R_{Th} \times 0.368$.
τ

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